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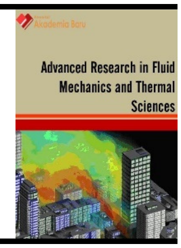

Parametric Study of Thermoacoustic System using DeltaE

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ABSTRACT

This work aims to study the parameters that had been used in designing a standing waves thermoacoustic rig for investigation of the turbulence characteristics in oscillatory flow. In this work, Design Environment for Low-amplitude Thermoacoustic Engines (DELTAEC) has being used to design the thermoacoustic rig. The voltage supplied and the frequencies were varied to predict the pressure and velocity at each segment. The data obtained had been compared with previous works for 10 to 60 Volt and drive ratio range of 9.0% to 10.3%. The results also reveal that increment of voltage amplitude by 10 volts caused deviation of data from 2.17 % to 20.35%, increment of velocity amplitude from 1.57% to 2.70%, and increment of drive ratio from 2.17% to 3%. The predicted critical Reynolds number occurred from the cone to the middle of the minor segments.

1.Introduction

In recent days, there are many research works based on green technologies as the greenhouse effect and climate change are in a very alarming state. However, due to the climate change, the refrigeration and air conditioning system become significant to the human lifestyle. The Chlorofluorocarbon (CFC) and Hydrocloroflorocarbon (HCFC) contained in these systems contribute to environmental problem. According to Montreal and Kyoto protocol, the usage of these refrigerants has their own restriction [1]. Because of this, scientist are trying to find a new ecofriendly refrigeration technologies that have a good coefficient of performance (COP) and low cost [2]. However, green technologies come at a great repercussion which is high in cost as a mean to acquire recent technologies. In order to overcome this problem, thermoacoustic technologies have been studied due to its environmental friendliness and also easy to handle as there are no moving parts which make them reliable and inexpensive. Thermoacoustic technologies create "thermoacoustic effect" which was first discovered in the 18th century by Byron Higgins [3]. This effect is created due to conversion between acoustic energy and thermal energy and vice versa. The performance of thermoacoustic technologies is affected by various operating parameters such as voltage supplied, geometrical parameters and working fluids which had been widely reported by previous

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investigations [3–7].There are two types of thermoacoustic refrigeration system which are based on the travelling waves and standing waves. The travelling waves are usually based in the large systems and standing waves are based in a simple compact system. In this study, the focused area is on the standing waves as the rig is more compact and also the flow that are being studied in the system is the oscillatory flow.

The thermoacoustic system consists of an acoustics driver such as loudspeaker attached to a tube and filled with the inert gases served as the working fluids. In addition, a stack which is known as the heart of the system was installed in a resonator. The working fluid oscillates within the resonator. In the resonator, the cooling effect could be increased as for example like acoustic power causes the contraction and expansion of the working fluid. Kinetic energy will be developed and transferred from one particle to another [9-10]. The fluid is expanded and compressed as the loudspeaker pumps the working fluid and the surface area of the stacks follows the thermodynamic principles and transfers the heat from the gas collision and produces heat energy. The acoustic power can be converted either to electric power or driven into a refrigeration system.

The thermoacoustic systems have been applied in electricity generation, electrical and electronic component cooling, mixture separation, automotive refrigeration and also in the space application. Although there are many benefits in the thermoacoustic system, there are also many drawbacks that have been not being studied. The turbulence effect, vortex formation, streaming, the entrance effect are some of the challenge in the system itself. A precaution should be taken where the system should be fully understood to prevent the thermoacoustic system performance from degrading gradually.

Oscillatory flows in the thermoacoustic system introduce so much complex understanding in order to know the flow pattern of the flow. There are description about the cooling cycle in the thermoacoustic system in many of the work that have been done by other researchers such as from Swift [11] and Braun *et al*.,[12]. Before designing any thermoacoustic rig, the researchers design the system using Design Environment for Low-amplitude Thermoacoustic Engines (DELTAE) software. DeltaE is a program that implements the design and the geometry of the thermoacoustic device so that the thermoacoustic system performances can be predicted [13]. The aim of this paper is to discuss the design of a standing waves thermoacoustic rig using DeltaE by varying the voltage supplied. The rig is specifically made for the detailed analysis of the pressure drop and the velocity effects. Besides that, the future works in the oscillatory flow rig are discussed in order to understand the lacks in the thermoacoustic systems.

2.DeltaE Modelling

DeltaE uses one-dimensional sequences of acoustic and thermoacoustic elements which is called as segments so the wave equation is in one-dimensional. The form of the *x*-independent cross-sectional area *A,* without viscous or thermal-hysteresis losses, it is represented in equation (1)

$$P + \frac{a^2}{\omega^2}\frac{d^2 p}{dx^2} = 0 \quad (1)$$

Equation (2) and (3) is the second-order equation of equation (1) where it is derived from the velocity and pressure.

$$\frac{dP}{dx} = -\frac{i\omega\rho_m}{A}u \quad (2)$$

$$\frac{du}{dx} = -\frac{i\omega A}{\rho_m a^2} p \tag{3}$$

The *dp/dx* equation is derived from the momentum equation of fluid mechanics and the *du/dx* equation is derived from the continuity equation of the fluid mechanics. These equations are utilized for the simultaneous integration along the axial position coordinate *x* to generate solutions of *p(x)* and *u(x).*

Basically, DeltaE integrates pressure in the spatial dimension using the low amplitude, acoustics approximation and also sinusoidal time impedance. In this paper, the study discusses about the pressure amplitudes, velocity amplitudes and also the Reynolds number. The fundamental physics that concerns the thermoacoustic theory can be described by the energy, continuity and also momentum equations which are the function of temperature, angular frequency, pressure volume flow rate amplitudes, system geometry and gas properties [11]. The relation of pressure amplitudes (p_1), mean temperature (T_m) and velocity amplitudes are represented using the equation 4 and 5,

$$\frac{dp}{dx} = -\frac{i\omega\rho_m}{A_{gas}(1-f)} u \tag{4}$$

$$\frac{dU}{dx} = -\frac{i\omega\omega_{gas}}{a^2\rho_m}\left[1 + \frac{(\gamma-1)f_K}{1+\varepsilon_s}\right]p + \frac{\beta(f_K - f_V)}{(1-f_V)(1-\sigma)(1+\varepsilon_s)}\frac{dT_m}{dx}U \tag{5}$$

where ω is the angular frequency which can be described as $2\pi f$ where the frequency is set in the DeltaE itself, ρ_m are mean density, T_m are temperature, P_m is pressure, c_p is isobaric specific heat capacity, γ is specific heat ratio, k is thermal conductivity, and σ is the Prandtl number of the working fluid. *Re*, *Im* and superscript ~ are the real part, the imaginary unit and the conjugate complex quantity respectively. $A_{gas}$is the flow area of the gas occupied of the channel and i is the imaginary unit. $f_v$and$f_k$are vicious and thermal functions depending on the geometry of individual component in the DeltaE.

3. Experimental Setup

Figure 1 shows that the cube-shaped loudspeaker box with dimensions of 600 mm x 600 mm x 600 mm is attached to a duct. In the current study, the arrangement of the rig includes a single loudspeaker which is in series with the cone attached to the resonator. The cone essentially reduces the internal square cross-section from 500 mm x 500 mm to 136 mm x 136 mm on its resonator end. The total length of the contraction is 300 mm. In this rig, the pressure is measured using pressure sensor at the end of the rig where it is called as antinode. The velocity is measured by using hot wire sensor as the point as shown in Figure 1.

3.1 Delta E Parameter Set-up

In the DeltaE, there are some parameters that can be determined based on the system design. In this parametric study, the frequency used is 13.1 Hz with air as the working fluid, and the drive ratio is based on the voltage amplitude that is being supplied to the loudspeaker itself. The drive ratios are being calculated using P_a/P_m where P_a is the oscillating pressure antinode and P_m is the mean pressure of the atmospheric pressure.

Table 1 shows the initial parameters used in the thermoacoustic systems with the mean pressure of atmospheric pressure and the room temperature. The area of the loudspeaker itself is 0.1m^2 with the resistance of 5.5 ohms. This paper is validated with the studies that have been conducted by Mmouet *et al*., [14].

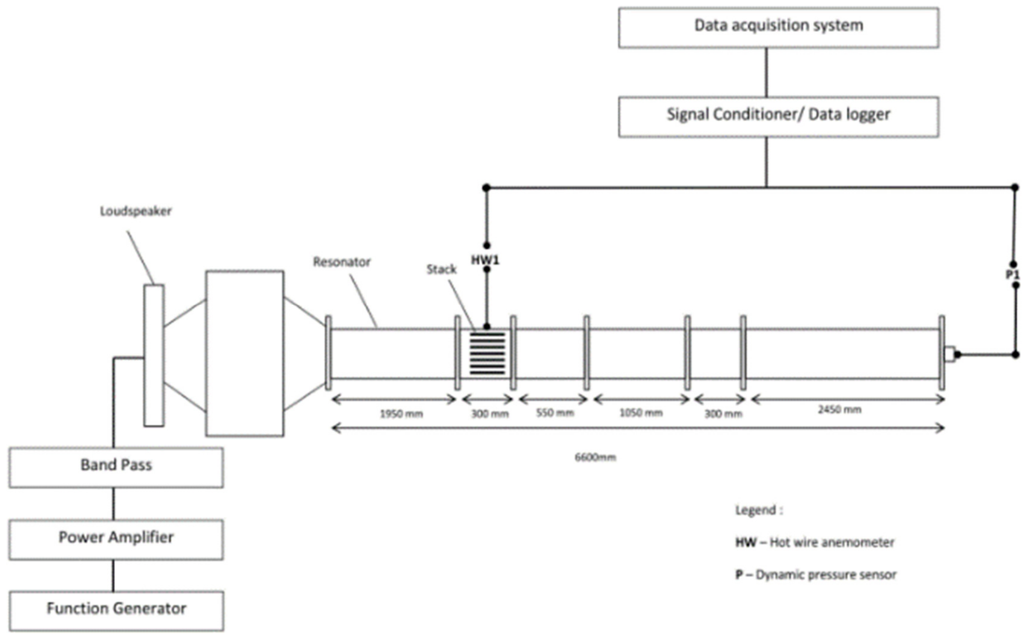

Fig. 1. The schematic diagram of the thermoacoustic system

Table 1
The initial parameters used in the thermoacoustic system

Parameters	Values
Frequency	13.1Hz
Mean Pressure	10133 Pascal
Temperature Beginning	296.15 k
Area of the loudspeaker	0.1 m^2
Loudspeaker resistance	5.5 ohms

There are six segments that have been used in the DeltaE which are begin, speaker, duct, cone, minor, long duct and hardened. From the Table 2, it is shown that there are seven segments total that have being usedand the location of the segment in the rig. The antinode of the rig is at the end of the rig where the pressure sensor is mounted.

Table 2
Location of each segment from the antinode

Segments	Location from the antinode (m)
BEGIN	8.30
Speaker	8.30
Duct	7.70
Cone	7.48
Minor	7.46
Long duct	7.4
Hardened	0

The segments labeled 0 BEGIN shows that the rig is set up with atmospheric pressure and also room temperature. It is also at the first part of the rig where the loudspeaker is placed and mounted. The first segment is the loudspeaker where the acoustics power is being supplied. The second segment is the duct where the loudspeaker box is placed and the third segment is the cone which is also known as the reducer. The forth segment is called the minor to connect the reducer and the 300mm long duct. The fifth segment is the long duct and the last segment is the hardened where the pressure sensor is mounted. All these segments are represented along in Figure 2.

4. Results and Discussion

4.1 Validation of the Data

Table 1 shows the resulting drive ratio calculated from the supplied voltage amplitude that is being supplied to the loudspeaker mounted at the rig. From Table 3, it is shown that the higher the voltage, the higher the drive ratio. This is because as the voltage increases, the acoustics power supplied generates an excitation towards the air particles. This results in the increase in pressure due to the particles gaining kinetic energy from the wave propagation of the air. The pressure increased causes an increment to the drive ratio.

Table 3
Comparison of the drive ratio with the other work

Voltage Amplitude (Volts)	Drive Ratio (P_a/P_m)	Drive ratio [14]	Deviation (%)
40	9.7 %	8.06%	20.35
50	9.9 %	9.69%	2.17
60	10.0 %	11.22%	10.81
70	10.3 %	12.75%	19.22

4.2 Variation of Pressure, Velocity and Reynolds Number

Figure 2 shows the predicted pressure at the outlet of each segment in the thermoacoustic system. The increasing of the percentage area causes the decreasing of the pressure and vice versa. The percentage of the reducing area at the cone to the minor is 7.39% and causes the pressure to increase significantly at the minor outlet. The pressure slightly drops at the beginning of the rig as the surface area is slightly increases in the cone area as compared to the first segment.

From the fundamental of the pipe flow, the pressure loss can be described in equation (6)

$$\Delta p_{friction} = \frac{32\mu L V_{avg}}{D^2} \quad (6)$$

where is μ the viscosity of the fluid, *L* is the length of the rig, *V* is the volume of the segments and *D* is the diameter of the rig itself. As the length of the segments becomes longer, the pressure slightly decreases and this can be shown in the duct in the segment 2 and also at the long duct. The pressure in this rig is the highest at the end of the cone, due to decreasing area of the cone. It is also shown that, as the pressure decreases, the velocity increases. This is the relation of the conservation of the energy that relates the pressure, kinetic energy and potential energy along the same elevation height.

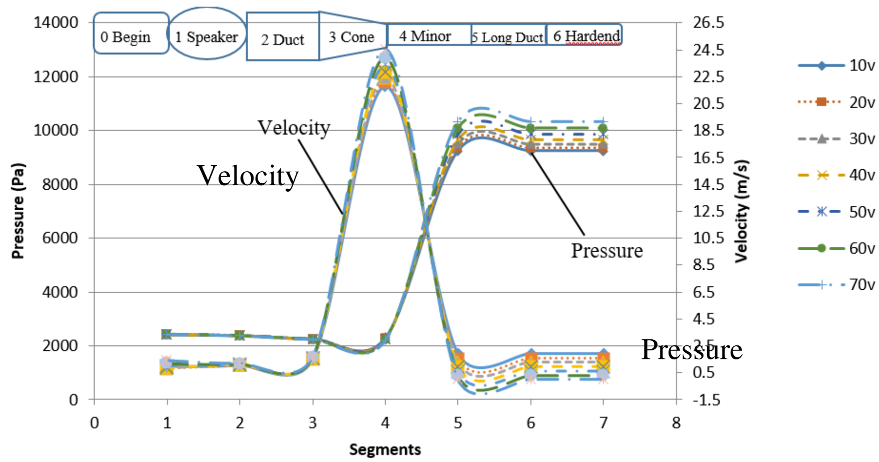

Fig. 2. The predicted pressure and the velocity at the end of each segment

Along the flow there are some minor losses predicted to occur in any connectors or region with different cross section area. These losses can be presented using equation (7)

$$\Delta p_{min\,or\,loss} = -\frac{1}{2}K\rho u^2 \quad (7)$$

where *K* is the minor-loss coefficient, ρ is the fluid density and u is the velocity. Since the flow inside the rig is oscillates, the minor segments is added that have two inputs for its *K* which define to be positive *K* for the direction of the flow in the *+x* direction and *K*is negative in opposite directions. From the analytical solution [11], the velocity is given in the equation (8)

$$u = \frac{k \cdot p_a \sin(kx)}{\Phi \omega p_m}\sin(\omega t)\cdot \mathrm{Re}[1-h_v] + \frac{k \cdot p_a \sin(kx)}{\Phi \omega p_m}\cos(\omega t)\cdot \mathrm{Im}[1-h_v] \quad (8)$$

where *k* is the wave number given by ω/c. *C* is the speed of light of 346 m/s. ρ_a is the pressure amplitude and in this equation, the value are using the drive ratio. Φ is defined as porosity of the thermoacoustic system. Table 4 shows the predicted velocity amplitude from the DeltaE and the theory that calculated from the equation (8).

Table 4
Table of voltage amplitudes versus drive ratio and velocity amplitudes

Voltage Amplitudes (V)	Drive Ratio (P_a/P_m) x100%	Velocity Amplitude (m/s)		
		DeltaE	Theory	Deviation
10	9.2	21.8067	22.6207	3.59 %
20	9.4	22.0656	23.1124	4.52 %
30	9.5	22.4111	23.3583	4.05 %
40	9.7	22.8383	23.8500	4.24 %
50	9.9	23.3439	24.3417	4.10 %
60	10.0	23.9222	24.5876	2.70 %
70	10.3	24.5683	25.3253	2.98 %

Figure 3 represents the predicted Reynolds number that is calculated from the velocity from Figure 2. From Turbulence in oscillating tube shows up as it surpass its critical value [15]. In the oscillating pipe flow, the Reynolds Number is defined as equation (9)

$$Re = 2u/\sqrt{v\omega} \tag{9}$$

Where u is the velocity amplitudes, v = is kinematic viscosity and ω is radian frequency. In this equation, the kinematic viscosity of temperature is 296.15 K. The kinematic viscosity that is being used is 1.5387 e^{-5} while the radian frequency is 82.31. Due to Merkli, the critical value for the *Re* is 400 [15]. Figure 3 show that the comparison of the velocity amplitude of predicted value from the DeltaE and the calculated value from the theory. The deviation is very small which lies in the range of 2.70 % to 4.52%. For the oscillatory flow, the critical value of Reynolds the critical value of 400 is reached at the center of the second duct to the cone and to the center of the minor. This happens at all various voltage amplitudes used and it is shown that turbulence is reached in this thermoacoustic system.

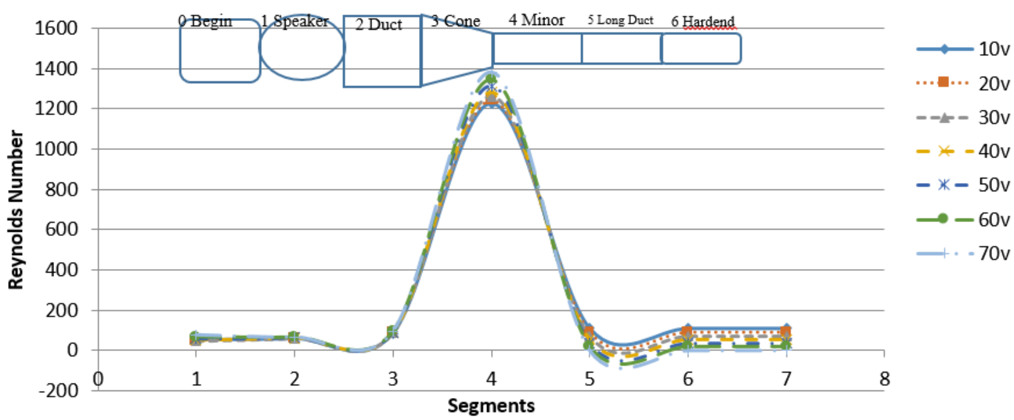

Fig. 3. Reynolds Number at the outlets of each segment

5. Conclusions and Future Work

The design parameters that have been used for investigating the thermoacoustic system have been discussed in this study based on the linear thermoacoustic. It can be seen that as the voltage is increased, the measured drive ratio increased too. The velocity, pressure and the Reynolds number versus the segments in the thermoacoustic system have been illustrated in this paper. In order to increase 1%-2% of the drive ratio, the voltage supplied should be increased by about 10V. The turbulence is predicted to occur at critical Reynolds number of 400 [15] and there are some turbulence effect occur in this thermoacoustic system. However, the experimental works that are being developed during the study of this work are limited mostly because the limitation of the loudspeaker and the test rigs itself. The test rig that has been built cannot withstand the vibration due to its material and its holder. Besides that, the loudspeaker that is being used is only the normal subwoofer that has limitation of the voltage that can be supplied to it. The future work will focus on the designation of the thermoacoustic system that is appropriate to the limitation of the loudspeaker and the test rig from the lab. The work also will be focus on investigating the turbulence characteristics at low voltage amplitude less than 10 volt and less than 3% drive ratio in order to reduce the lacks in the thermoacoustic systems.

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